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LIGHTWEIGHT RECOVERABLE COSMIC-RAY DETECTORS

A Film Badge Dosimeter

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SCHOOL OF AEROSPACE MEDICINE
USAF AEROSPACE MEDICAL DIVISION (AFSC)
BROOKS AIR FORCE BASE, TEXAS

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A Film Badge Dosimeter

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CORRECTIONS

("Lightweight Recoverable Cosmic-Ray Detectors: A Film Badge Dosimeter," by Loren C. Logie, Joseph S. Pizzuto, John E. Pickering, and Fred Yablinsky, School of Aerospace Medicine Report 62-28, Feb. 1962)

1. Page 3, column 2, line 12: Sentence should be changed to read--

   We used the values in table III in determining . . .

2. Page 7, column 2, lines 20-21: Sentence should be changed to--

   . . . tool in the space cosmic-radiation-detection program . . .

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INTRODUCTION

As it became necessary for us to provide radiation detection equipment for rocket and balloon space-probing flights, we began to study the feasibility of various passive radiation-detection systems applicable in absence of telemetering facilities. Three requirements were immediately apparent: the detector must be small and lightweight; it should be highly sensitive in order to detect the radiation levels ordinarily encountered in space; and it should be quickly and easily evaluated.

Film appeared promising as a recoverable radiation dosimeter for use in space probes. In addition to being highly sensitive to electromagnetic radiation, small and lightweight film had long been used as a basic radiation-detection tool at this laboratory.

Film is generally used for roentgen-ray detection, although it is known to respond to other radiations. It is highly energy dependent below 0.3 Mev as demonstrated by Deal et al. (1). Since its radiation–energy dependence makes interpretation difficult, film dosimetry has proved adequate only with proper calibration and knowledge of the effective energy of the radiation.

Workers have suggested the possibility of using two or more filters with different absorption properties to determine the effective energy of a radiation (2-5). Tochilin et al. (2) were among the first to describe a film dosimeter which could be used to detect the quality of incident x-radiation. Their device consisted of stepped wedges of different thicknesses of aluminum and copper in combination with photographic film. Baker and Silverman (3) described a somewhat similar detector utilizing lead over silver. Storm and Bernis (4) report a device using several filtering media over the film and discuss the response of the film to electromagnetic radiations with energies through 10 Mev. Davis and Hart (5) describe a combination film dosimeter-personnel-identification badge, in use at the Oak Ridge National Laboratory, which uses the calibrated response of film to several filtering media.

Since the possibility of varying energy, electromagnetic radiations exist in the space capsule (because of the interaction of cosmic radiations with the space vehicle), a film detector dosimeter was designed to measure the secondary radiations. This device is similar to that described by Tochilin et al. (2). The filtering materials and number of steps used in our detector was designed to provide energy information below 0.3 Mev. Above 0.3 Mev the energy dependence of film is reduced so that errors in the interpretation of dose are minimized.

In an effort to incorporate the dosimeter into the space-probing, cosmic-ray detection program, its response has been calibrated against several different radiations. This paper describes the stepped-metal film detector used, its response to several different radiations, and its use as a cosmic-ray detector. The energy information that can be obtained

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This work was accomplished at the Radiobiological Laboratory of the University of Texas and the United States Air Force, Austin, Tex.

for proton and alpha radiations is also discussed. Size and weight limitations did not allow the use of a larger number of thicker filters to provide a greater range of proton and alpha energy information.

MATERIALS AND METHODS

The stepped-metal, film-packet dosimeter that we constructed consists of Dupont film type 552 (personnel monitoring film). It is divided into four areas shielded as follows: area A, unshielded; area B, 0.020 in. Al; area C, 0.020 in. Al and 0.008 in. Cu; area D, 0.020 in. Al and 0.024 in. Cu. The metal echelon array is placed both in front and behind the film with the aluminum inside the copper. Two emulsions are present in the Dupont 552 film packet (emulsions 502 and 510). Since nearly all the readable densities of 510 film are a linear function of the radiation dose received and since the 502 film does not respond in such a linear fashion, only the 510 emulsion was chosen for investigation.

Film processing was performed in a constant-temperature bath maintained at 68° ± ½° F. The films were developed with F-R Corporation rapid speed x-ray film processing developer for a period of three minutes, rinsed in 68° F. water, fixed with F-R Corporation fixer for 10 minutes, and then washed in water for 30 minutes. Density determinations were obtained from a photovolt model 400R densitometer calibrated against a standard density wedge. The calibration was checked before and after each reading.

The radiation source used in the x-ray calibration of the Radiobiological Laboratory film dosimeter (RBLD) was a Picker deep therapy 260 kvp x-ray unit with an inherent filtration of approximately 1½ mm. Al. Additional radiation parameters at each of the effective energies used in this study are given in table I.

Ten or more films were exposed at each of the x-ray calibration points. Variations in the density of film exposed with the same radiation parameters but processed at different times were as much as ± 50 percent. To compensate for this variation in density, a radiation-control film was always processed with each set of films. The radiation-control film was given 1 r of x-radiation with the Picker x-ray machine operating at 130 kvp filtered through 1 mm. of Al and 0.25 mm. of Cu. These radiation-control films have had an average net density of approximately 1.6. As a standard procedure, therefore, all net densities were corrected in the same proportion needed to raise or lower the net density of the radiation-control film to a value of 1.6. Even though this procedure was followed, corrected net densities varied considerably (± 20 percent) for film given the same dose at the same effective energy but processed at a different time.

In addition to the x-ray calibration, the RBLD was also calibrated with Co^{60} gamma radiation, with 14 Mev protons, with 730 Mev protons, and with 900 Mev alpha particles. A small NBS calibrated Co^{60} source was used for the Co^{60} gamma radiation calibration. The

TABLE I

Added radiation parameters for 10 different effective energies

Kvp	Added filter	Kev (effective)
50	0.812 mm. Al	24
50	0.254 mm. Cu 0.508 mm. Al	34.5
76	0.914 mm. Cu 0.813 mm. Al	46
150	0.25 mm. Cu 1 mm. Al	57
200	0.25 mm. Cu 1 mm. Al	67
250	0.25 mm. Cu 1 mm. Al	80
250	0.5 mm. Cu 1 mm. Al	93
150	1.067 mm. Sn 3.200 mm. Cu 0.965 mm. Al	106
200	0.762 mm. Pb 2.515 mm. Sn 1.143 mm. Cu 0.965 mm. Al	173
250	2.159 mm. Pb 1.321 mm. Sn 1.118 mm. Cu 1.016 mm. Al	198

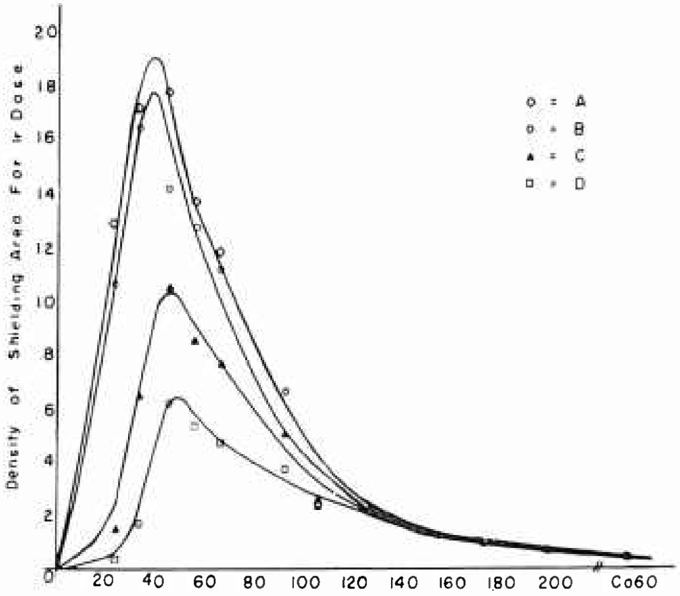

FIGURE 1

Corrected net densities of the shielding areas A, B, C, and D for the RBLD versus effective energies of x-radiation.

14 Mev protons for calibrations were obtained from a H^2 (He^3 He^1)H^1 reaction using a 2 Mev Van de Graaff accelerator. The 730 Mev proton and 900 Mev alpha calibrations from the synchrocyclotron were obtained at the University of California Radiation Laboratory, Berkeley, Calif. The density of the film exposed to Co^{60} gamma radiation, 14 Mev protons, 730 Mev protons, and 900 Mev alphas was always corrected in a manner similar to that used in the x-ray calibrations. The density variance for the film exposed to the latter four radiations was considerably smaller than that for film exposed to x-rays. Therefore, as few as two films per calibration point were used for these radiations.

RESULTS

The net densities of the areas designated A, B, C, and D versus effective energy of x-radiation are given in figure 1. These densities are representative of a radiation dose of 1 r. In table II, the experimental values of the density ratios of adjacent shielding areas and corresponding multiplying factors are labeled MF/B, MF/C, and MF/D. Multiplying factors indicate the amount by which the corrected net density under a shield must be multiplied so that the exposure received can be converted to roentgens. Density ratios versus multiplying factors are also plotted in figure 2 while the density ratios of adjacent shielding areas versus corresponding effective energies are shown in figure 3. The information in figures 2 and 3 provides the data needed to determine the effective energy and the radiation dose received by an RBLD from an unknown radiation.

We used the following values in determining radiation dose and effective energy with this detector.

In determining dose and effective energy, first, calculate the ratios for the corrected net densities for A/B, B/C, and C/D. These are the following: A/B, 1.08; B/C, 1.61; C/D, 1.67. Since the ratio C/D is the largest, this ratio is compared to the curve labeled C/D in figure 3. This ratio corresponds to an effective energy of 51 kev. The radiation dose may be determined by consulting the curve labeled C/D in figure 2 to find the multiplying factor (MF/D). A multiplying factor (MF/D) of 1.9 is found

TABLE II

Density ratios and multiplying factors versus effective energies

Energy	Density ratio A/B	Multiplying factor MF/B	Density ratio B/C	Multiplying factor MF/C	Density ratio C/D	Multiplying factor MF/D
24	1.20	0.93	3.0	2.78	3.46	7.69
34.5	1.07	0.56	2.18	1.22	2.64	3.23
46	1.05	0.71	1.56	1.08	1.77	1.89
57	1.04	0.94	1.37	1.30	1.56	1.96
67	1.04	1.15	1.27	1.54	1.41	2.22
93	1.03	2.38	1.09	2.63	1.17	3.23
106	1.03	2.57	1.04	2.70	1.10	4.0
173	1.01	10.0	1.01	10.0	1.03	10.0
198	1.0	12.5	1.0	12.5	1.02	12.5
Co^{60}	1.0	20.0	1.0	20.0	1.0	20.0

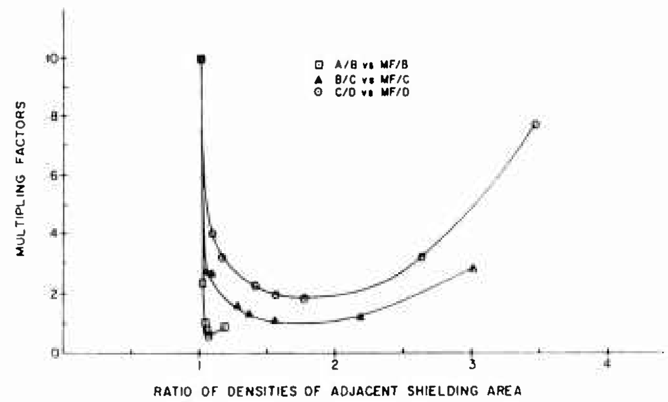

FIGURE 2

Density ratio of adjacent shielding areas of the RBLD versus multiplying factors.

for the C/D curve at a ratio of 1.67. The product of MF D (1.9) and the net density of D (.40) yields a radiation dose of 0.76 r. The data in table III are from an actual exposure that was taken from an RBLD x-ray exposure at 0.75 r with an estimated effective energy of 50 kev.

In addition to the x-ray exposures, the RBLD was calibrated with four other radiations. One of these four radiations was 14 Mev protons which produced an observable stepped-density effect limited to the unshielded area (A) and the first shielding area (B). Apparently, the shielding material covering areas C and D is large enough to prevent most of the 14 Mev proton radiation from reaching the

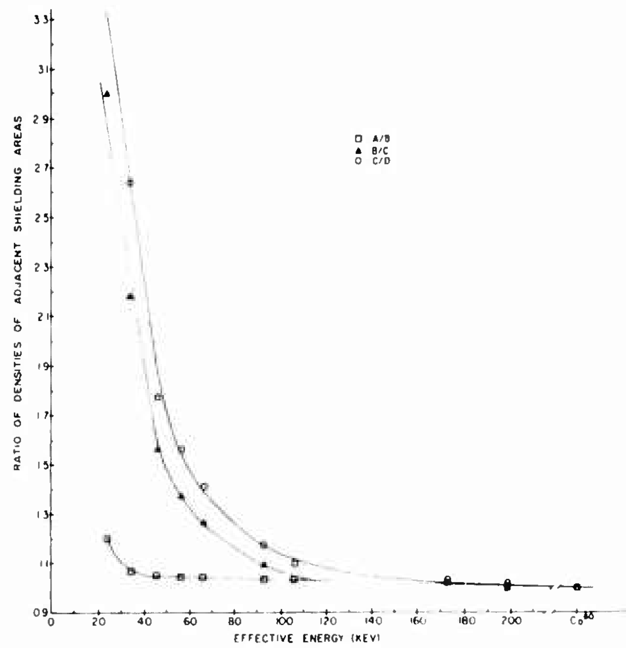

FIGURE 3

Density ratio of adjacent shielding areas of the RBLD versus effective energies.

TABLE III

Data from an actual exposure

	Areas			
	A	B	C	D
Corrected densities	1.17	1.08	0.67	0.40

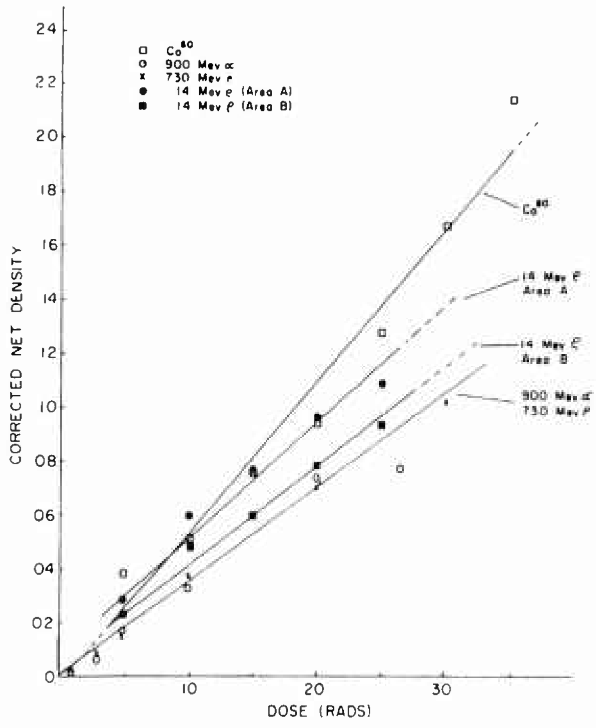

FIGURE 4

Corrected net densities of the RBLD versus radiation dose for Co^{60} gamma, 14 Mev protons, 730 Mev protons, and 900 Mev alphas.

film. Consequently, only the corrected densities for the two shielding areas (A and B) versus corresponding radiation dose for the 14 Mev proton radiations are plotted in figure 4. Film was also exposed in the RBLD to three other radiations (Co^{60} gammas, 730 Mev protons, and 900 Mev alphas). A stepped-density effect for film exposed to these radiations was not observed. Therefore, the corrected net densities for the entire film area are used to illustrate the relationship between film density and radiation dose for Co^{60} gammas, 730 Mev protons, and 900 Mev alphas. The relationship between film density and radiation dose for these three radiations is also plotted in figure 4.

DISCUSSION

Aside from its use in determining radiation dose, the RBLD, below 200 kev, provides a simple and direct method for measuring the quality of electromagnetic radiations. Although one might not ordinarily expect to find electromagnetic radiations in space, one should expect roentgen radiation to be produced as one of the secondary products in the interaction of cosmic radiations with the space vehicle. The detector system described in this article, the RBLD, provides a rapid means for determining the energy of these secondary radiations. An error can occur in the interpretation of the effective energy of an unknown radiation. The film density response of the RBLD to low-energy radiations maximizes at an energy somewhat greater than zero. Therefore, the same density ratio may occur at two different energies. An error in determining the dose may be introduced by choosing the effective energy, but Tochilin et al. (2) conclude that these errors are not excessive.

The usefulness of the RBLD was tested by exposing it successively to x-radiation at two different energies. Two energies from the two extremes of the energy response curve were used to provide the most difficult test possible. First, an RBLD was given a dose of 1 r of x-radiation with an effective energy of 34.5 kev. It was then irradiated a second time to another dose of 1 r using x-radiation with an effective energy of 173 kev. The corrected net densities for the four shielding areas, A, B, C, and D, were, respectively, 2.44, 2.44, 1.40, and 0.64. The ratios as calculated from these data were A B, 1.0; B C, 1.74; C D, 2.19. Since the density ratio for C D at 2.19 was highest, C D in figure 3 shows the apparent effective energy. Accordingly, the two radiations in this particular combination have an apparent effective energy of 46 kev. In figure 2, the MF D for a C D ratio of 2.19 is 2.40. Using the multiplying factor of 2.4 and the corrected net density for D at 0.64, one obtains a dose of 1.47 r. Since the density-energy dependence of film is emphasized more at the lower effective energy (34.5 kev) than at the higher effective energy (173 kev) the detector should be expected to underestimate the dose. The example given clearly emphasizes the difficulties that may occur when film is used to determine a dose.

As a further test of its usefulness, the RBLD was exposed to 0.5 r of x-radiation with

an effective energy of 67 kev. The corrected net densities for the four shielding areas (A, B, C, and D) were, respectively, 0.60, 0.58, 0.41, and 0.31. From this information, the ratios for A/B, B/C, and C/D were, respectively, 1.04, 1.41, and 1.32. The ratio B/C at 1.41 is largest. This ratio corresponds to an effective energy of 58 kev as shown in figure 3. According to figure 2, the multiplying factor (MF/C) for a ratio of B/C at 1.41 is 1.5. The product of the multiplying factor (1.5) and the density of C (0.41) is the dose evaluation of 0.61 r. Although the film dosimeter underestimated the effective energy by 15 percent, it overestimated the radiation dose by 20 percent.

The examples indicate the usefulness of the RBLD to determine dose in a low-energy, electromagnetic radiation field. Since this device is planned for use in space probes some of the problems concerning its use in space should be clarified.

The stepped density that will be produced on film by particulate radiations is a range-energy function, dependent on the type of particle and on the thickness and composition of the shielding material. One would expect the stepped effect to disappear when the resultant energy of the particle through the shielding material approaches the energy of the unshielded particles. For the shielding materials used in the RBLD, the energy points where the stepped effect occurs and disappears are as follows:

At low energies (below 9 Mev) the proton lacks sufficient energy to penetrate the thinnest shield and reach the film. At intermediate energies (9 to 45 Mev) the protons will produce a stepped effect on the film because of the difference in specific ionization of the particles that reach the film through the different shields. At higher energies (50 to 60 Mev) the specific ionization of the shielded proton is essentially the same as the unshielded proton resulting in a uniform density across the film.

The specific ionization of protons is approximately one-fourth that of alpha particles. Theoretically, one would expect the conditions described above to exist at energies about four times that reported for protons. Because of the nonlinearity of range-energy curves, comparable effects for alpha particles occur at energies approximately three times that of the proton energies.

Admittedly, there are some limitations to the use of the RBLD as a radiation detector for space probes. For instance, in a mixed irradiation field of high-energy particles (with varying energies) and low-energy, electromagnetic radiation, results obtained could be erroneous. If the particulate energies were great enough to produce a uniform density behind all shields, a constant error would be superimposed on the stepped densities produced by the low-energy, electromagnetic radiations. This would cause a decrease in the density ratios, resulting in an error in interpreting the dose. On the other hand, should the particulate energies be low enough to produce their own stepped-density effect the interpretation of densities would be more difficult since a variable error would be added to the low-energy, electromagnetic densities. The RBLD will be used with other dosimeters, however, and it is believed that the combination of devices will furnish a method for interpreting the RBLD information.

Secondary irradiations produced in the step shields are not likely to complicate interpretation of results when the composition of the radiation field is known. The effect of secondaries would not be a problem since this effect has been included in the calibration with high-energy protons and alpha particles. There is no reason to expect the effect of secondaries to be dependent on the source of the high-energy particles (in space or man made).

The radiation detector, RBLD, described in this paper, has been flown on two separate occasions in high-altitude space probes. In one space probe, it was flown on the Discoverer XVII rocket. Although there appeared to be a slight gradation in density across the film,[1] it did not appear as a marked stepped-density effect. This absence of a stepped-density effect

[1] Processed by the Physics and Engineering Section, Radiobiological Laboratory, Austin, Tex.

was interpreted to mean that no detectable low-energy, electromagnetic radiations were encountered or created during this flight. Also, since the stepped effect was not noted, the density of the film was correlated to a dose of high-energy protons (730 Mev) and high-energy alphas (900 Mev). It should be noted that the correlation between film density and dose for the two high-energy radiation calibrations are nearly the same. Therefore, either of the two calibrating radiations may be used. Cosmic-ray authorities agree generally that most of the radiation at the Discoverer XVII flight altitudes (103 nautical miles perigee and 538 nautical miles apogee) is either high-energy protons, high-energy alpha particles, or a combination of these two. Therefore, the dose correlation in terms of these two radiations appears correct (6). In addition to the ambient radiation normally found in space, solar-flare radiations were apparently encountered by the Discoverer XVII rocket (7). Correlating the film density of the RBLD's flown in this rocket either to high-energy proton or to alpha radiation still appears correct, however, since the radiation resulting from the solar flare is primarily high-energy protons. The average corrected net density of the film flown in the Discoverer XVII flight indicates a dose of 30 rads using either the proton or the alpha dose calibration in figure 4. This evaluation is in agreement with dose determinations found with the other detector systems flown in this rocket which ranged between 25 and 30 rads.

The RBLD was also flown in the Discoverer XVIII rocket. The corrected net density for the film flown on this rocket was 0.02. The very small but consistent change in density for the experimental film flown in this rocket suggests that the assignment of a dose is questionable; however, other types of detectors also flown on this rocket tend to support the assignment of 0.6 rad high-energy proton or alpha dose as found with the RBLD.

Although the Discoverer XVIII stayed aloft considerably longer than the Discoverer XVII rocket, the radiation dose encountered by the former seems considerably less than that encountered by the latter. The difference in the level of the radiation dose encountered by the two rockets can apparently be attributed to the absence of a solar flare during the Discoverer XVIII flight; whereas, the Discoverer XVII rocket was flown during a major solar flare.

The worth of the RBLD as a cosmic-ray detector for rocket and balloon flights is indicated by its success. Many of the radiation detectors used in these two flights were too insensitive to detect the relatively low levels of radiation. The importance of the radiation sensitivity of the RBLD cannot be overemphasized since radiation fluxes in space are generally low. In addition to its radiation sensitivity, the compactness and lightness of the RBLD fall well within the requirements dictated by rocket and balloon payload limitations. The RBLD thus appears to be a unique and valuable tool in the space-cosmic, radiation-detection program at the School of Aerospace Medicine.

SUMMARY

A film badge dosimeter (RBLD) has been devised to provide a rapid method for determining effective energies below 200 kev of an unknown electromagnetic radiation. The dose response of the RBLD has been calibrated to x-radiation at several different effective energies as low as 24 kev to 198 kev. The film used in this dosimeter (the 510 emulsion) is the insensitive one of the 552 Dupont film packet. Data have been included in this report correlating film densities with dose for four high-energy radiations. These radiations were Co^{60} gamma, 14 Mev protons, 730 Mev protons, and 900 Mev alphas. A method to reduce film density variances arising from small differences in film processing is also described. A pre-exposed radiation-control film is developed simultaneously with each set of experimental films. The net densities of the experimental films are then raised or lowered in the same proportion needed to give a net density of 1.6 for the radiation-control film.

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